NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

IMPLEMENTATION OF A TWO-PROBE TIP-TIMING
TECHNIQUE TO DETERMINE COMPRESSOR BLADE
VIBRATIONS

by

Nicholas Glen Osburn

June 2000

Thesis Advisor: Raymond Shreeve

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13. ABSTRACT *(maximum 200 words)*

This study involved the implementation and validation of a blade-tip time of arrival (TOA) measurement technique, and the development of a computer program to analyze TOA data using a recently published approach. The program was used to analyze experimental compressor data taken in-house using two laser light probes, data generated computationally, and data obtained by others in a compressor test. The in-house compressor data was compared successfully to amplitudes obtained by strobed digital photography. A resonance was successfully detected in the supplied compressor data set.

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IMPLEMENTATION OF A TWO PROBE TIP-TIMING TECHNIQUE TO DETERMINE COMPRESSOR BLADE VIBRATIONS

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Ensign, United States Navy
B.S., United States Naval Academy, 1999

Submitted in partial fulfillment of the
requirements for the degree of

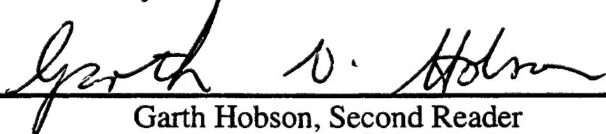## MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

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June 2000

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ABSTRACT

This study involved the implementation and validation of a blade-tip time of arrival (TOA) measurement technique, and the development of a computer program to analyze TOA data using a recently published approach. The program was used to analyze experimental compressor data taken in-house using two laser light probes, data generated computationally, and data obtained by others in a compressor test. The in-house compressor data was compared successfully to amplitudes obtained by strobed digital photography. A resonance was successfully detected in the supplied compressor data set.

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I. INTRODUCTION

A.   BACKGROUND

The overall aim of current research related to engine high cycle fatigue (HCF), is

to develop the capability to predict, and consequently avoid, HCF-related failures of

turbine and compressor blades. New testing procedures are required that will involve

both excitation of vibrational modes in the blading of spinning rotors, and the

measurement of the blades' response. The present work deals with the problem of

measuring the blade response, using a technique that does not require instrumentation to

be in contact with the blades.

B.   CONCEPT

Non-contact measurements of rotating turbomachinery are well documented,

some dating to the early 1970's (Zablotsky, 1970). The current experimental system

employed two laser probes peripherally separated but at the same axial station over the

blade tips. By determining the exact time required for each blade to pass from a

reference position to the sensors, the deflection of the blade from its mean position could

be determined. From such time of arrival (TOA) data, the harmonic oscillation of each

compressor blade, at varying shaft speeds, may be determined.

The present study involved the implementation and validation of the measurement

technique and the development of a computer program to analyze TOA data using a

recently published approach (Heath, 1999). The program was used to analyze

experimental compressor data taken from optical sensors, data generated

computationally, and data obtained by contractors in a compressor test in another

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laboratory.[+] The in-house compressor data was also compared to amplitudes obtained by digital photography, in order to validate the TOA measurements.

C.   BENEFITS

The thesis project will benefit the Navy, and other organizations and companies interested in affordable high cycle fatigue testing. However, the project's immediate purpose is to provide non-contact HCF-related blade vibration measurements in the Naval Postgraduate School's rotor spin pit. The technology developed will be transitioned to the Naval Air Warfare Center Aircraft Division, to be used in HCF-related rotor spin testing.

[+] Hood Technologies Corporation supplied the data from tests conducted at Wright Patterson Air Force Base. This cooperation is acknowledged and is appreciated.

II. TEST APPARATUS AND DATA ACQUISITION

A. COMPRESSOR AND BLADING

The test facility was a 36-inch diameter, two-stage compressor mounted horizontally in the laboratory. As is illustrated in figure 2.1, air was drawn from outside the building (through an inlet bellmouth mounted outside the wall) and exhausted into the room. The compressor was driven by a 150 HP synchronous motor with a nominal rotational speed of 1610 RPM. Due to the nature of the electric motor, speed variation could only be achieved by cutting the power to the compressor.

Figure 2.1 Compressor and wall mounted inlet.

A section through the compressor and the wall survey assembly are shown in Figures 2.2 and 2.3. To accommodate sensors over the tip of the second rotor, a matrix of 25 plug locations was machined in the case wall of the compressor (Moyle, 1991).[+] This allowed the angular separations between the two laser probes to be varied in increments of 2.8125 degrees, and the axial positions to be varied over the length of the

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[+] The wall survey assembly was designed to allow a single Kulite pressure sensor to be used for rotor surveys. The light probes in the present study were mounted in plugs that were identical to that used by the Kulite.
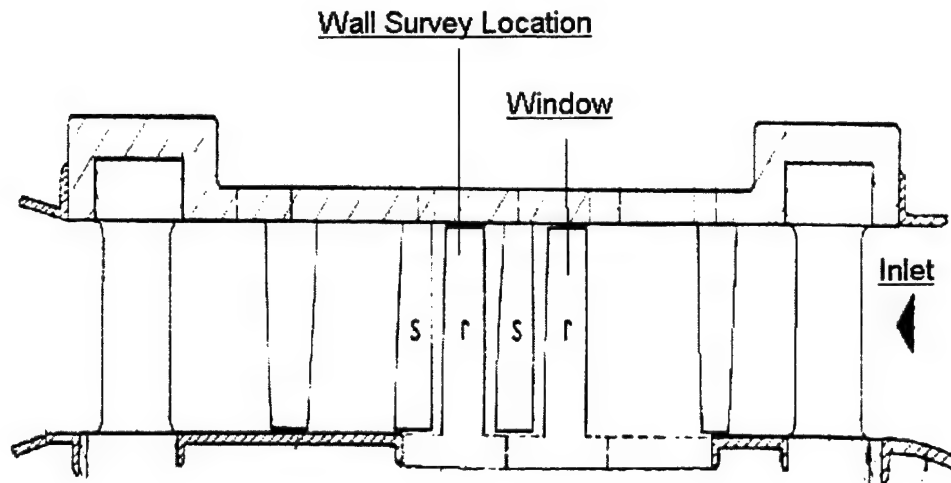
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Figure 2.2 Compressor diagram showing the locations of the wall survey assembly and Plexiglas window in relation to the rotor stages. From Moyle (1991)
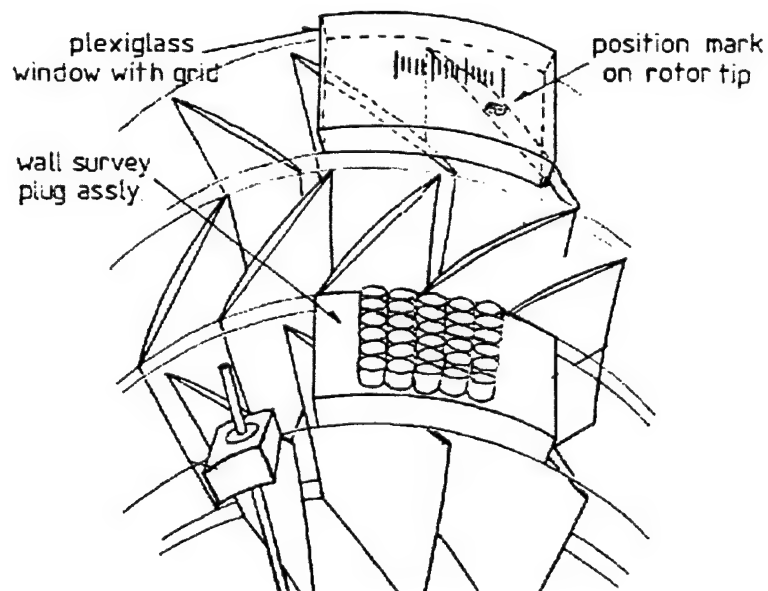
Figure 2.3 Detailed view of the wall survey assembly, window, and rotor blade with cross. From Moyle (1991)

rotor blades. Upstream of the wall survey plug assembly, a Plexiglas window, also visible in Figures 2.2 and 2.3, was located to visually observe the rotation of the first rotor stage. A red cross was drawn on one of the compressor blades of the first stage to serve as an angular reference for the experiment. Further technical information for the compressor is available in Moyle (1991).

The compressor blades were constructed by casting aluminum-filled epoxy resin in room temperature vulcanization silicone rubber molds. The blade profiles were based upon a circular arc camber line, with a thickness distribution that was flattened at the leading edge. Each blade was cast around a steel shank and threaded bolt, with glass cloth and carbon fiber to reinforce the root. Complete design information is available in Vavra (1970), while construction is detailed in Moyle (1981).

B.   LASER LIGHT PROBE SYSTEM

A schematic of the instrumentation and the data acquisition system is shown in Figure 2.4. The data acquisition station for the light probe measurements is shown in Figures 2.5 and 2.6.[+] A strobe (not shown in the figure), and the 'Delayed Pulse' feature of a Wavetek Model 145 function generator were used to position a rotor blade, with a red cross at its tip, in the center of the Plexiglas window and concurrently initiate Time of Arrival (TOA) measurements with a one-per-rev signal. A four-channel Hewlett Packard Infinium oscilloscope was used to set-up and monitor the acquisition process. The laser probe system used for the project was manufactured by Integrated Fiber Optic Systems Incorporated, of Stony Brook, New York (Dhadwal, 1999).

[+] The four channel system was provided on loan by the instrumentation group of Wright Pattersen Air Force Base

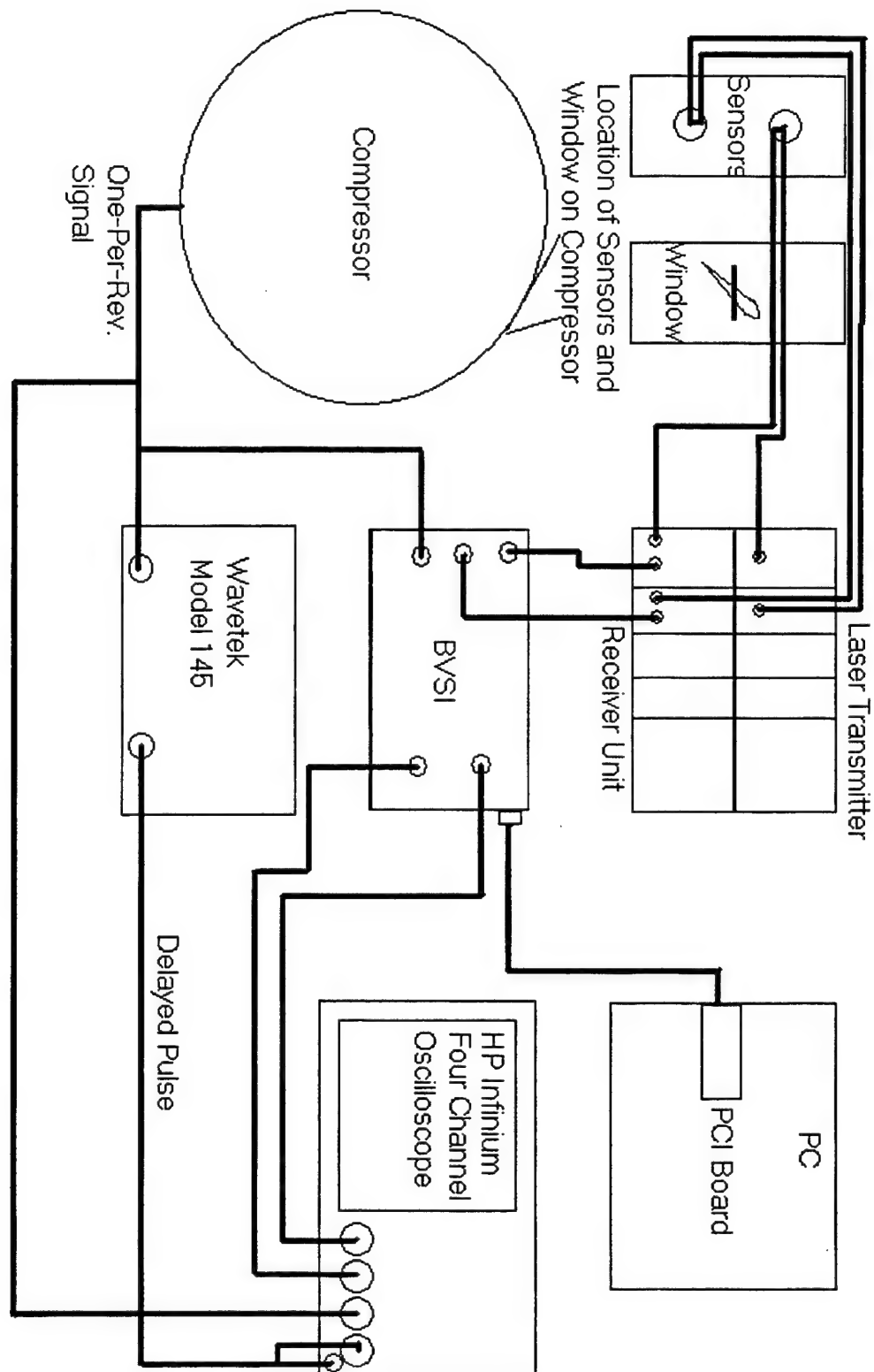**Figure 2.4** Schematic of the Instrumentation and Data Acquisition System.

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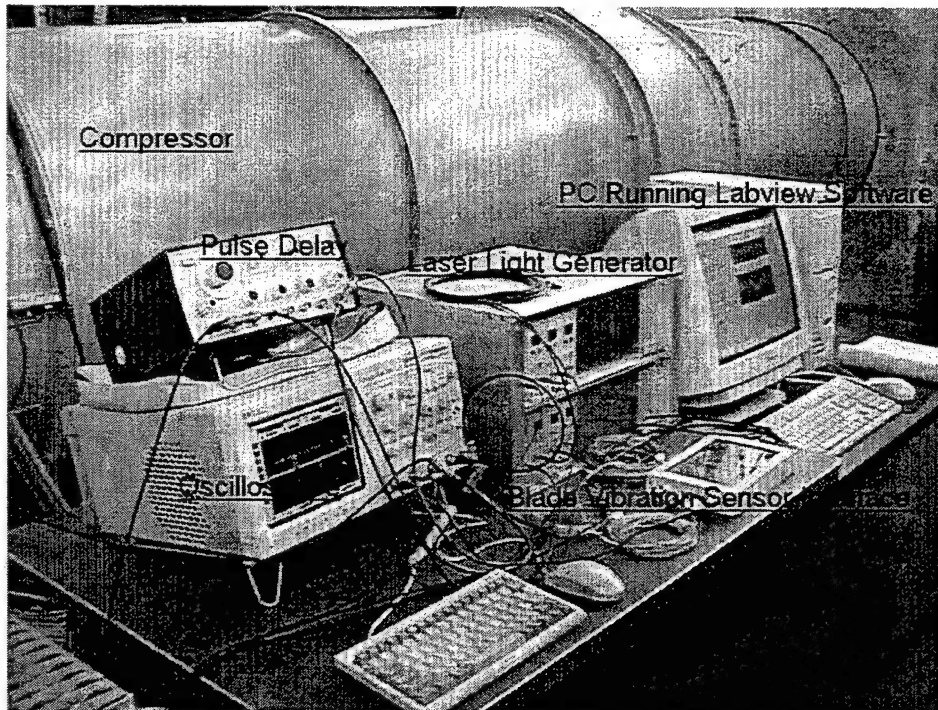
Figure 2.5 Test apparatus showing data acquisition equipment.
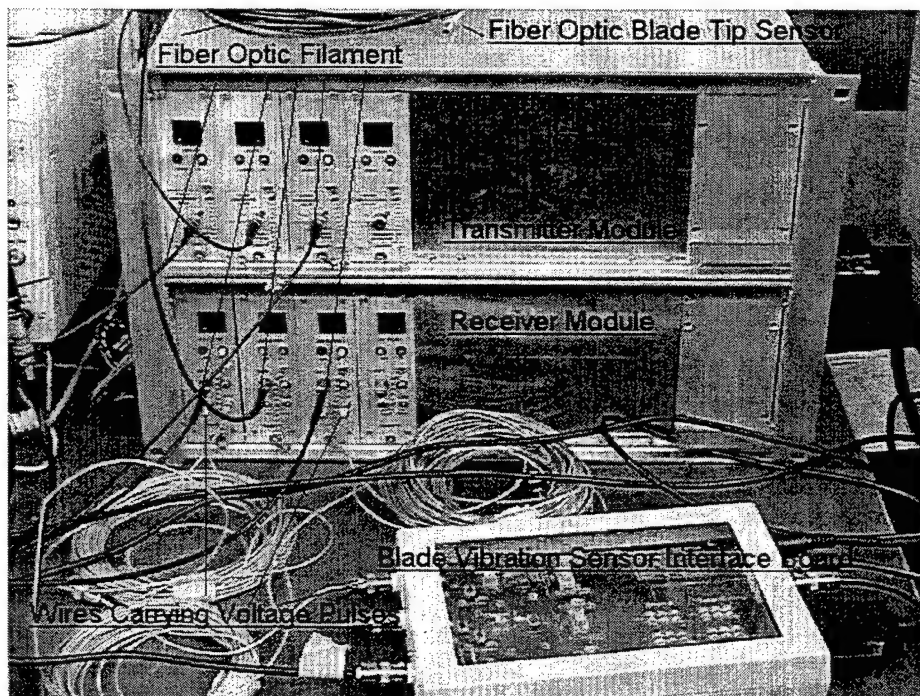
Figure 2.6 Laser Light Probe System and Blade Vibration Sensor Interface Board.

Each channel of the four channel system was composed of three elements; a transmitter module, the fiber optic blade tip sensor, and a receiving module. The transmitter module operated as a continuous laser light source for the sensor. Through fiber optic filaments, the laser light was delivered to the tip sensors where it struck each compressor blade, of the second rotor stage, as it passed the wall survey assembly pictured in Figure 2.3. At the passage of each blade, the light reflected from the blade tip was received by collecting fibers, and transmitted to the receiving module. The receiving module produced either analog voltages or square pulse signals that were input to the Blade Vibration Sensor Interface. Figure 2.6 depicts the transmitter and receiver modules rack-mounted with power supplies manufactured in house.

C.   BLADE VIBRATION SENSOR INTERFACE (BVSI) AND DATA ACQUISITION

The Blade Vibration Sensor Interface was designed by the Hood Technology Corporation of Hood River, Oregon (Figure 2.6). A picture and details of the board are given in Appendix A. The purpose of the interface was to receive a one-per-rev and two tip-timing analog pulse trains, and to output corresponding time accurate TTL pulses to a National Instruments PCI counter board in the PC. The board was expressly designed to allow the conversion to digital pulses to be controlled (with adjustments to arming and trigger levels on each channel), and to allow the selection of which signals to interrogate on two oscilloscope channels. It must be noted that to avoid identifying extra blade pulses, the arming and triggering levels must be set at their lowest possible voltages to prevent triggering on blade tip imperfections.

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The Blade Vibration Monitoring (BVM) Labview software for the PC (provided by Hood Technology Corporation) allowed the user to monitor the performance of the sensor systems in real time. The control window is shown in Figure 2.7. Once the start button was clicked, the software began recording data and continued until the stop button was pressed. The software then prompted the user to name the files and designate a location to save them. The automatic reduction of this TOA data by the software then converted the data for each blade to measurements of thousandths of an inch, and stored this information in the designated files. The software required the input of the rotor diameter, the angular positions of the two probes, and the angular position of the first rotor blade. The derivation of these precise angular measurements is described in Appendix B1. A sample raw data file is present in Appendix B2.
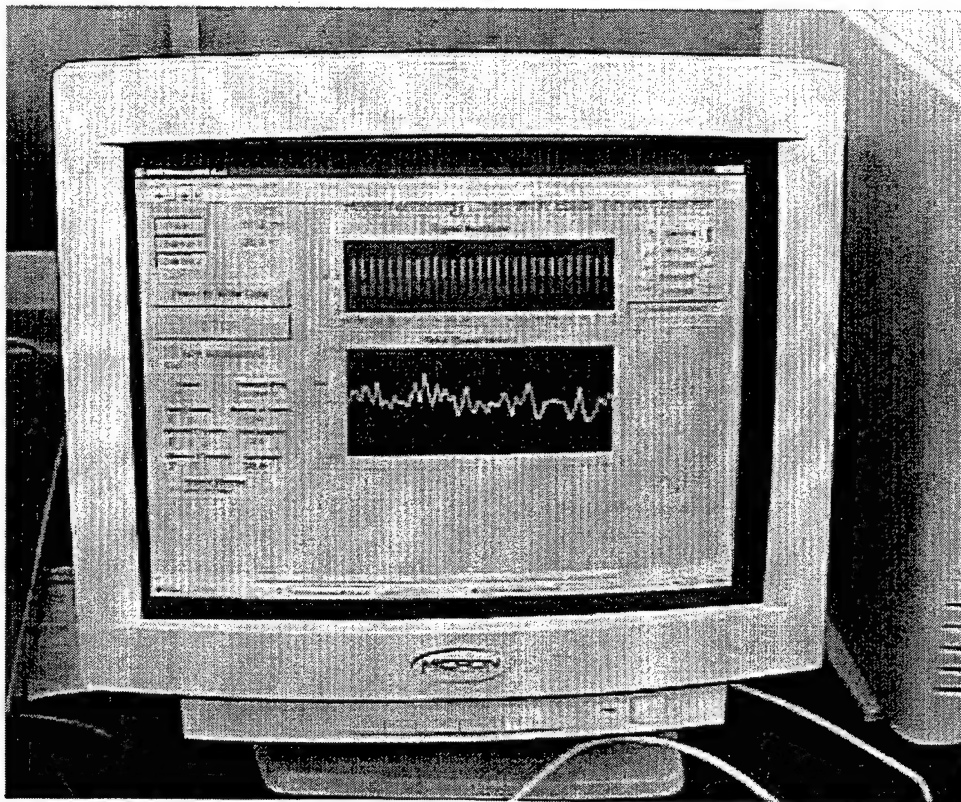
Figure 2.7 Labview Software on PC.

III. DATA ANALYSIS

A. METHOD OF ANALYSIS

After initial examination of the amplitude of tip motion, the method of analysis developed by Heath was programmed to derive frequencies and amplitudes of resonant behavior from TOA measurements (Heath, 1999). The procedure requires the acquisition of two sets of tip-timing measurements from optical probes mounted at the same axial plane in the case wall. By plotting the tip-deflection data for a particular blade, taken when the compressor is transitioning a resonance, for two probes, one against the other, both the resonance order and the maximum amplitude of the resonance can be determined. Figure 3.1 illustrates this method. The plotted data for the blade deflections forms a near ellipse. Through the method of least squares, a smooth curve is fitted to the data and the lengths of the major and minor axes are measured. The ratio of the minor axis to the major axes is a measure of the engine order of the resonance.
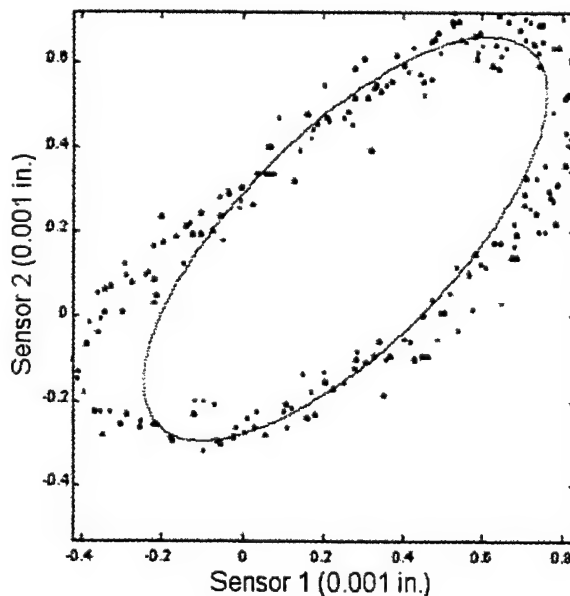
Figure 3.1 Heath's Method.

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B.   PROGRAM DESCRIPTION

Matlab was used to implement the method of analysis (Appendix C1) described above, and to program a test data generator (Appendix C2). The necessity for the latter will be described in greater detail in the following chapter. The Matlab language was chosen because of its compatibility with the data generated by the Labview software, the ease with which its programs can be modified, and its superb graphical analysis tools. Both programs are fully documented in the Appendix C.

IV. EXPERIMENTAL PROGRAM AND RESULTS

A.   OVERVIEW

Following the integration of the sensor system with the compressor test rig, and the completion of the analysis software, the entire system was tested to ensure the accuracy of the blade displacement measurements output by the analysis program. A digital camera was fixed above the Plexiglas window, and digital movies were taken of blade 1 as it was flashed by a strobe light. The strobe was triggered by the delayed one-per-rev pulse. The digital movies were then analyzed, using a PC to display each strobe-illuminated frame. The blade's displacement, with reference to the gradations etched in the window, was measured, and the results compared to those given by the analysis program.

Once the displacement measurements were validated, a spare rotor blade was bowed to identify its resonant frequencies. A Campbell diagram, generated earlier using a similar rotor blade was used to verify the results of the bowing. Transient tests were then conducted by cutting power to the compressor while recording TOA data. The results given by the analysis program, were then compared to those expected from resonant crossings on the Campbell diagram. Indications of resonance were found, but the deceleration rate was too rapid to allow a clear definition of frequency and amplitude.

Since the deceleration rate could not be controlled, in order to test the validity of the analysis program, an artificial data generator was created in Matlab. This program, listed in Appendix C2, was used to simulate the data that would result from the behavior of a resonating rotor blade. Using an error function, the amplitude of the blade's vibration about its mean position could be set to maximize at a selected frequency. By

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successfully analyzing the artificially generated TOA data file, the accuracy and utility of the analysis program were verified.

Finally, a series of TOA data files were obtained from the Hood Technology Corporation. The files contained data that was taken during compressor tests conducted at Wright Patterson Airforce Base. These files were analyzed by the analysis program as a last check.

B.   SYSTEM VALIDATION WITH DIGITAL PHOTOGRAPHY

The goal was to compare blade vibration amplitudes derived from TOA measurements by the analysis program, and amplitudes obtained by direct measurement, through the use of a digital camera. The camera was fixed to a rigid bracket that was attached to the compressor case just below the Plexiglas window. The bracket enabled the camera to be positioned perpendicular to the window, and to be held firmly in position during the compressor's operation. A series of digital movies in an 'mpeg' format were then taken while the compressor was running at constant speed, and converted to still 'jpeg' images using a PC and 'Paint Shop Pro' software. Figures 4.1 and 4.2 show images taken on successive revolutions, as converted jpeg images. The motion of the compressor blade is clearly evident between the two pictures. (The gradations etched into the window have been computer enhanced). In order to define a mean position for the blade during the compressor's operation, the red cross drawn on the tip was aligned with the bottom gradation, while the tip of the leading edge was aligned with the center gradation. Adjusting the time delay of the pulse controlled the visible position of the blade. The deviation of the blade away from this mean position shown in the second picture represents the maximum for this run.

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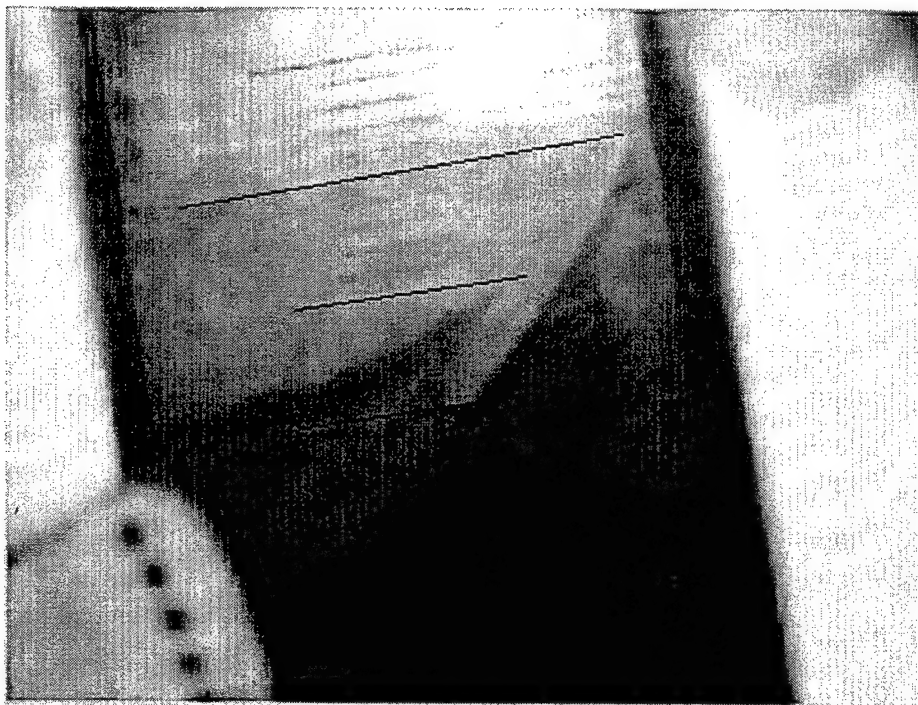
Figure 4.1 Mean blade position during compressor operation.
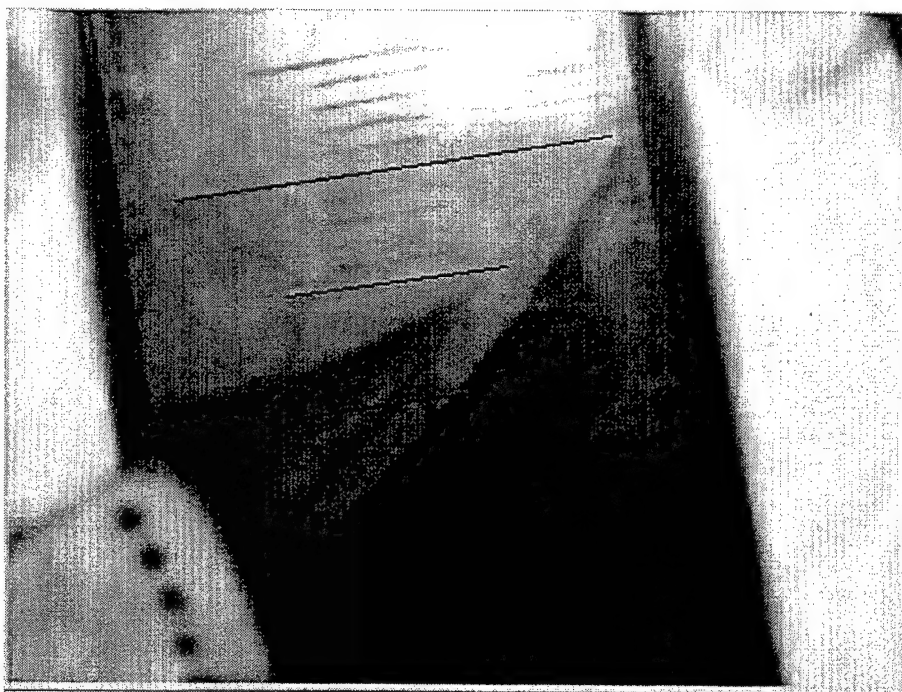
Figure 4.2 Maximum deviation away from the mean.

The (enhanced) gradations were 0.5 inches apart on the Plexiglas surface, and the width of the red cross was approximately 0.05 inches. Using these measurements to scale the displacements visible on the PC image (using lengths in numbers of pixels), the maximum movement of the blade for this particular run was determined to be approximately 0.03 inches. The corresponding displacements recorded by the two sensors and output by the analysis program for this same run, are shown plotted in Figure 4.3. It can be seen that the maximum amplitude derived from the photographs, and that deduced from probe TOA measurements, were in close agreement. Although the pictures (taken through the Plexiglas window), and the sensors record separate stages of the compressor, the behavior of the blades for each stage is similar. A plot depicting amplitude versus time, at constant speed, for both sensors, showing blade number one is presented in Appendix D1, while a plot showing data for all thirty blades per sensor is illustrated in Appendix D2.
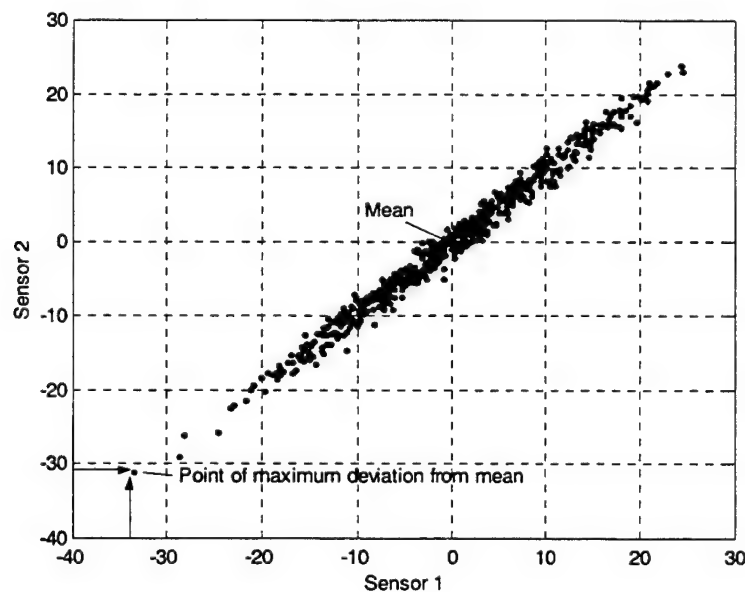
Figure 4.3 Constant Compressor Speed Results for the Displacement of Blade 1.
(Scale is in 0.001 inches).

C.   IDENTIFICATION OF BLADE RESONANCES

Potential blade resonance was determined by bowing a compressor blade to establish modal response, and constructing the Campbell diagram for the blade. The Campbell diagram for the present rotor blade is shown in Figure 4.4.[+] Typical results of bowing the blade are shown in Figure 4.5. The figure shows the FFT of the amplified sound produced by bowing.
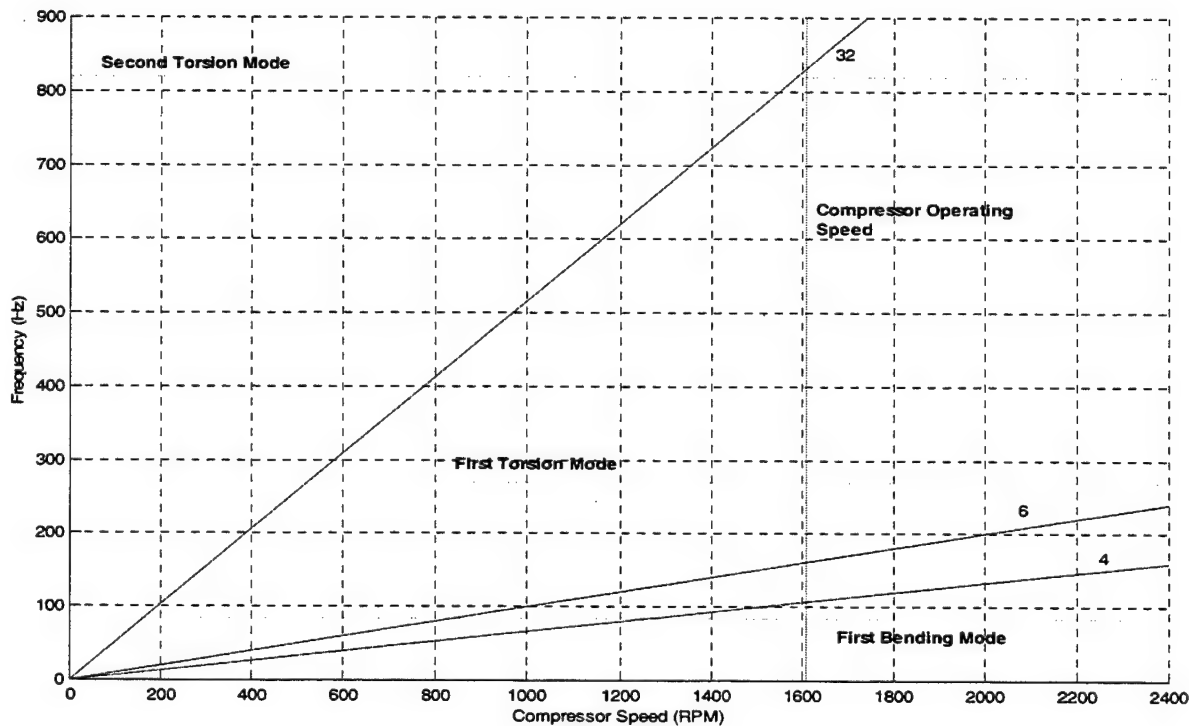
Figure 4.4 Rotor Blade Campbell Diagram.
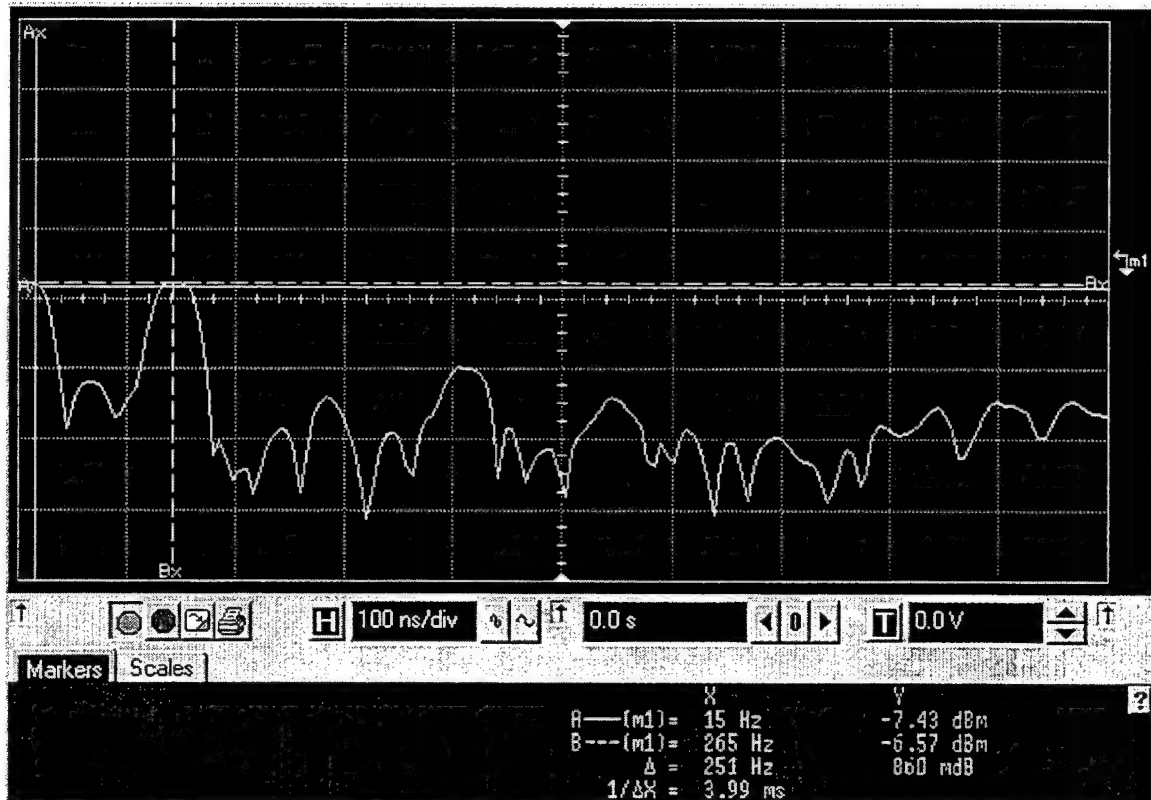
Figure 4.5 Frequencies excited by bowing a rotor blade.

D. ANALYSIS OF RESULTS WITH DECELERATION

Compounding the problem of being unable to control the deceleration (the electric drive motor was synchronous and could not be adjusted), the damping caused by the air flowing through the compressor restricted the excitation of the blades as they transitioned the resonances. Figure 4.6 shows the results of a deceleration.
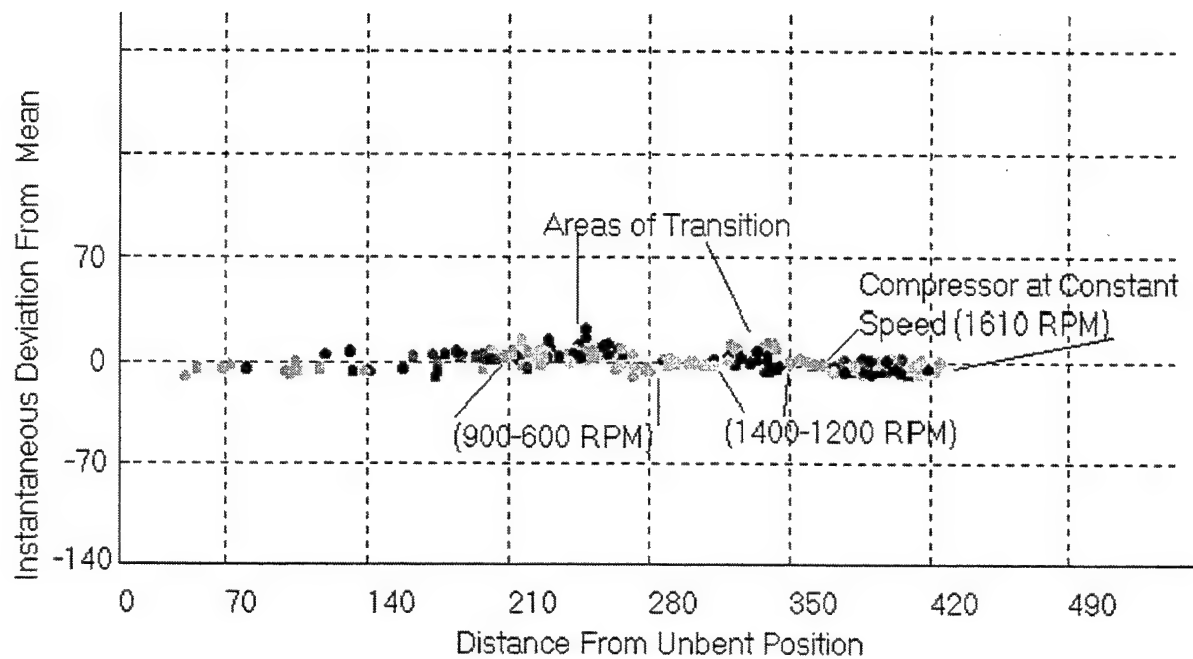
Figure 4.6 Compressor deceleration results
(Scale is in 0.001 inches).

In Figure 4.6, the x and y axes have been rotated -45 degrees so that the 45 degree slope line lies along the x axis. This was done to enable the major and minor axes of any resulting ellipses to be more easily measured (Heath, 1999). The string of data points represents the blade unbending as the compressor slowed. The y-axis depicts the deviation away from the mean bending line. The points clustered to the far right were taken at the constant operating speed of approximately 1610 RPM. Data points for speeds below approximately 400 RPM could not be plotted because of hardware limitations. (The data points were plotted in groups of ten, with neighboring groups possessing different colors.) Zero on the graph is the approximate unbent position of the blade. Due to the uncontrollable deceleration and dampening, the regions where the compressor transitions blade resonances appear only as areas of unpronounced excitation.

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These groupings of data points occurred between 1400-1200 RPM (23.33-20 Hz), and 900-600 RPM (15-10 Hz). When compared to the Campbell diagram these speeds correspond to the fourth and sixth engine order crossings of the first bending mode. The torsional crossings apparent in the Campbell diagram were not detected due to their smaller amplitudes and the effects of damping in the compressor

E.   ANALYSIS OF TEST DATA

To ensure that the analysis program was functioning properly, an artificial data set was generated to simulate a resonating compressor blade. The complete program is listed in Appendix C.2. Using an error function, the program generated a data file that, when plotted, created a figure that spiraled out to form an ellipse when a specific frequency was transitioned. The test data was designed to simulate the first bending mode at the 900 RPM crossing of the rotor blade. Figure 4.7 shows the results of analyzing the test data. As is illustrated by the ellipse fit to the test data, visible in blue, despite the deliberate addition of noise to the program, the original parameters were deduced.

Deceleration Range:
1610 to 300 RPM

Resonant Frequency:
900 Hz

Minor Axis:
3.033×10^{-3} in.

Major Axis:
10×10^{-3} in.

Probe Spacing:
9 degrees
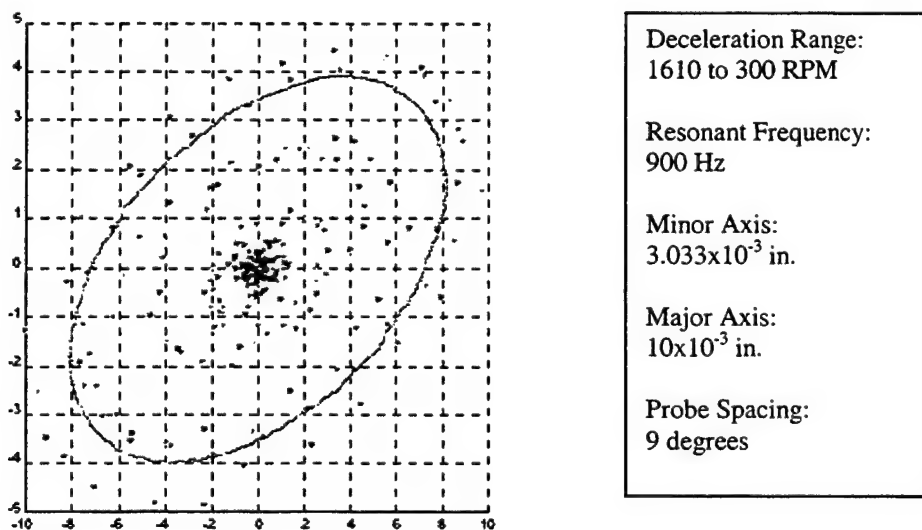
Figure 4.7 Analysis of Test Data (0.001 in. per division)

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F.   HOOD TECHNOLOGIES DATA

The data files provided by Hood Technologies from vibration tests at Wright

Patterson Airforce Base enabled the analysis program to be further tested. The data files

were generated with better controlled test conditions than was possible with the

compressor at the Postgraduate School. However, some processing of the raw data was

required before the application of Heath's method was successful. After a process of trial

and error it was found that an eighth order polynomial to smooth the TOA data for each

blade, and averaging the rotor speed over the operating time, provided reasonably noise

free results. Figure 4.8 depicts the results of plotting the data files for blade one against

one another after implementing the smoothing process. The outline of an ellipse is

clearly visible. By narrowing the field of data input to the analysis program, the ellipse

was found to be generated between 12960 and 13000 RPM. Figure 4.9 shows the results

of restricting the window, and Figure 4.10 shows the ellipse fit by the analysis program,

in applying Heath's method.
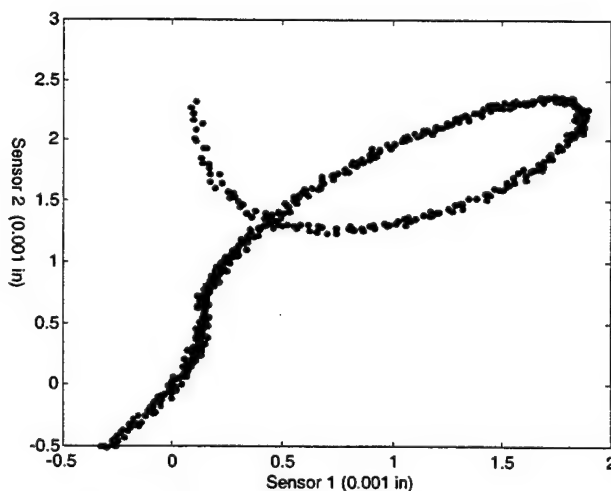
Figure 4.8 Analysis of Hood Technologies data file from tests conducted at Wright
Patterson AFB

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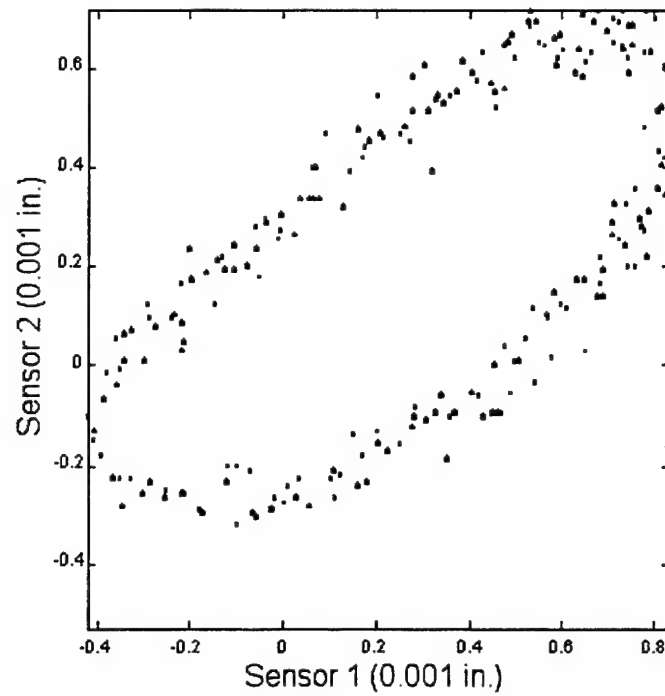
Figure 4.9 Ellipse at resonant rotor speed (12960-13000 RPM)
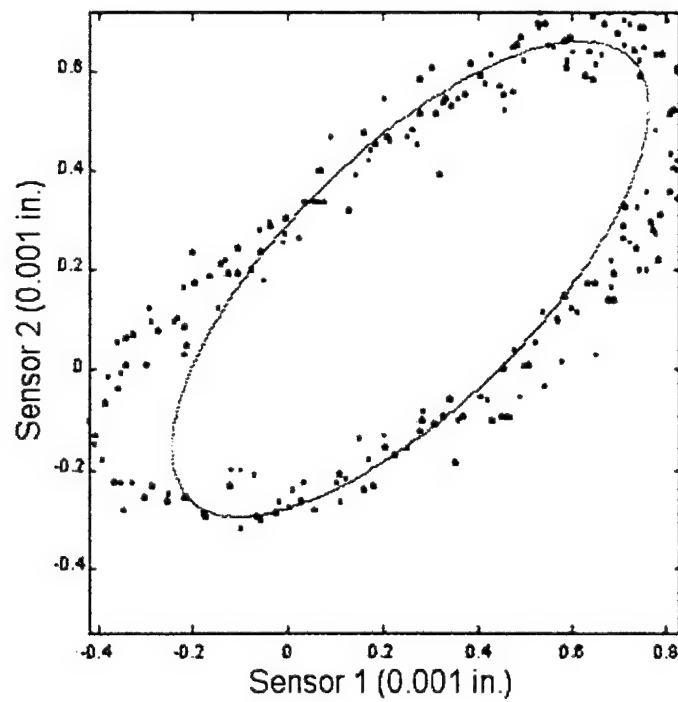
Figure 4.10 Ellipse fit for Heath's Method

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Applying Heath's method to the axis ratio, the vibration was correctly identified as a fourth engine order resonance at approximately 13000 RPM, and the amplitude may be easily read from the displacement scale. It is noted that the peak amplitude of the blade vibration was only 0.002-0.003 inches, which is an order of magnitude smaller than was measured in the NPS low speed compressor. Thus the method is capable of identifying blade resonances in the NPS transonic compressor, which has a rotor diameter of eleven inches, and in similar, and all larger, rotors which are to be tested in the HCF/Spin Test research program.

The ellipse of data points in Figure 4.10 is canted slightly down on the left side because the sensors were not placed on the same axial plane. It is noted that Heath's method requires that the sensors be on the same axial plane. The reason that the resonance was found successfully with the present data is that the resonance was a bending mode. Indeed, the attempts to identify reported non-bending modes in the data set, were not successful.

V. CONCLUSIONS AND RECOMMENDATIONS

A two-channel laser light probe system was implemented successfully to obtain blade tip timing, 'time of arrival' (TOA) data on a low-speed compressor. The amplitudes of tip deflection measured by the system were successfully verified using strobed photography. No significant problem was encountered in using light probes with the BVM interface board and acquisition software, which were developed and used by Hood Technologies with other types of sensors. The completed system constitutes the 'front-end' of a 'non-contact stress measurement system' (NSMS) (Jones, 1996), which can now be used in the HCF/Rotor Spin Research Facility.

The method of Heath, to detect and identify blade resonance from TOA data, was programmed and used successfully to identify a blade resonance in compressor test data acquired from the Hood Technologies Corporation. It was found that data smoothing procedures were required before the method gave definitive results on the supplied data set. However, the amplitudes involved were very small, (0.002-0.003 inches), and smoothing may not always be necessary. Attempts to identify blade resonance from data taken in the NPS Low Speed Multi-Stage Compressor were not successful because the deceleration of the compressor could only be effected by cutting power, generating too-rapid a deceleration. Confidence in the programmed analysis method was established, however, by programming the calculation of a virtual data set for a compressor decelerating through a blade resonance, and then identifying the programmed resonance using the analysis. The programmed calculation of data can be used to investigate the robustness of the analysis method.

With the knowledge gained thus far, recommendations are to:

-Implement the probe and acquisition system in the Rotor Spin Research Facility

and obtain data as specific resonance conditions are deliberately excited in the

blades.

-Solicit and analyze other acceleration or deceleration data sets (containing

resonant behavior) which were acquired with probes located at the same axial

plane.

It is noted that the data acquired in spin-testing, in which the rotor is hung on a slender

spindle, may require a different analysis than data from compressor tests, in which the

rotor is spun between nearly rigid bearings. Thus the recommendations should be

followed consonantly.

APPENDIX A. HOOD TECHNOLOGIES BLADE VIBRATION SENSOR INTERFACE BOARD
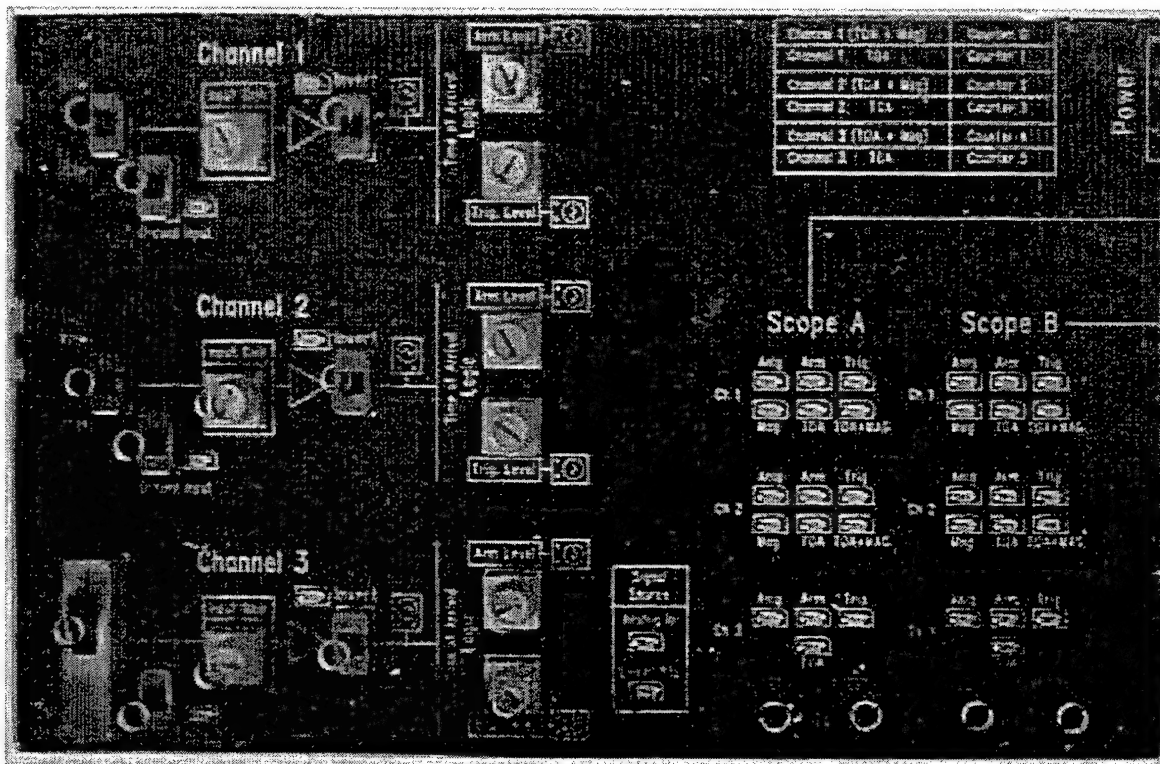
Electric Characteristics:

Power In:

Ground	DIN Pin 1
+5VDC <500mA	DIN Pin 3
-12VDC 300mA	DIN Pin 4
+12VDC 300mA	DIN Pin 5

Power In: **Use ELPAC WM113-TT**

Power Out:

Ground	Sub-D Pins 6,7,8,9
+12VDC	Sub-D Pin 4
-12VDC	Sub-D Pin 5

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APPENDIX B1. DETERMINATION OF ANGULAR POSITIONS FOR THE BVM LABVIEW SOFTWARE

The angular positions for each of the probes was measured using the machine drawings for the compressor to obtain key dimensions. The horizontal seam between the upper and lower sections of the compressor was used as the reference, with 0 degrees represented by the seam nearest the wall survey assembly. The probes were used in positions corresponding to 61.8750 degrees and 73.1250 degrees. (This was the greatest separation allowed by the wall survey assembly, and was used to provide the largest possible movement of the rotor blades between the sensors.)

The BVM Labview software required the input of the angle of the first rotor blade at the one-per-rev pulse. This angle was calculated by using the 'Delayed Pulse' function of a Wavetek signal generator. By inputting the one-per-rev pulse into the Wavetek, and delaying the pulse until the rotor blade with the red cross was visible in the center of the Plexiglas window, the timing difference between the one-per-rev pulse and the delayed pulse was measured to be 1.6727 ms (Figure B.1). (It is important to note that the Wavetek must output a negative pulse in order to operate the strobe.)   Since the center of the window was known to be 55 degrees in reference to the seam, and the compressor operated at a mean speed of 1611.8 RPM, the angle of blade 1 at the one-per-rev. (the rotor with the red cross) was calculated to be 43.9 degrees.
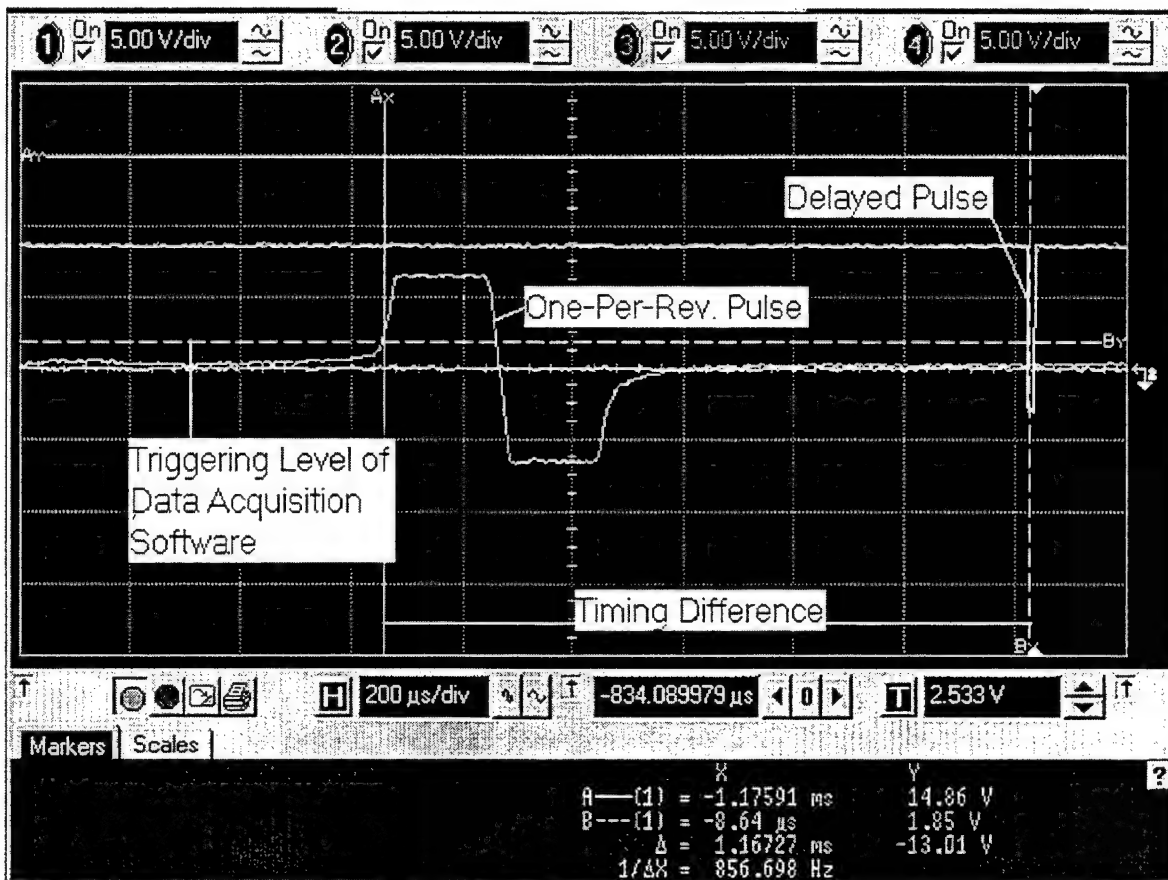
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Figure B1. Oscilloscope window for the determination of the timing delay.

APPENDIX B2. SAMPLE DATA FILE
(Data for blades 2-30 are not shown)

TIME (SEC)	SPEED (RPM)	TOA (BLADE 1) (0.001 in.)
67.1683	1566.6389	2069.1102
67.2453	1545.7225	2069.0547
67.2841	1539.0535	2069.022
67.3231	1525.2971	2068.9736
67.3624	1517.2876	2069.0472
67.402	1508.8304	2069.0623
67.4417	1498.5614	2069.2675
67.4818	1490.1575	2069.2455
67.522	1481.0975	2068.8792
67.5626	1471.692	2068.9103
67.6033	1463.5092	2068.9722
67.6443	1454.0537	2068.9208
67.6856	1445.4818	2068.7299
67.7271	1436.7111	2068.6569
67.7689	1427.7454	2069.0056
67.8109	1419.3524	2069.0659
67.8532	1410.5351	2068.9346
67.8957	1402.1591	2069.0483
67.9385	1393.513	2069.2825
67.9815	1385.0112	2069.0414
68.0249	1376.7262	2069.5362
68.0684	1368.1294	2069.5868
68.1123	1359.8042	2069.3454
68.1564	1351.5751	2069.9776
68.2008	1343.251	2069.886
68.2455	1335.2665	2069.9202
68.2904	1326.9478	2069.7727
68.3356	1318.9306	2069.677
68.3811	1310.6661	2069.8095
68.4269	1302.7025	2069.4447
68.473	1294.6534	2069.3891
68.5193	1286.6963	2068.7587
68.5659	1278.9673	2068.6411
68.6129	1270.9468	2068.175
68.6601	1263.1965	2067.928
68.7076	1255.4481	2067.684
68.7554	1247.5608	2067.4139
68.8034	1240.1152	2067.4827
68.8518	1232.0392	2067.4231
68.9005	1224.9085	2067.4052
68.9495	1216.9472	2067.6561

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APPENDIX C1. MATLAB IMPLEMENTATION OF HEATH'S METHOD

```
clear all;
%All previous variables are cleared

sen = input('Input the number of sensors currently in use:'
);
%The user is asked to input the number
%of sensors used.

for i=1:sen
%The for loop is initiated once for each sensor in use.

   in = input('Enter the name of the desired ASCII input
file with its extension:');
   s = load (in);
%The user is asked for a Labview ASCII file
%and it is read into Matlab.

   m = mean(s);
%The mean value of each column of the ASCII file
%is computed and saved as a row vector.

   [q,r] = size(s);
%The size of the ASCII file is computed: [rows,columns].

   for y = 3:r
     for z = 1:q
        dat(z,y-2) = s(z,y) - m(1,y);
     end
   end
%The tip-timing data for each blade is normalized about
%its mean position, calculated previously, by subtracting
%the mean for each blade from its respective column of
%values.  This data is saved into the matrix dat.

   e = num2str(i);
   d = ['in_' e];
   eval([d, '=in;']);
%Each ASCII file is saved under the variable in_(and the
%numberof its corresponding sensor).

   a = 'dat_';
   b = num2str(i);
   c = [a b];
   eval([c, '=dat;']);
```

```
%Each matrix of normalized tip-timing data is saved under
%the variable dat_(and the number of its corresponding
%sensor.)

end

blade=input('Enter the blade you wish to observe:');
figure(1)
x1=dat_1(:,blade);
y1=dat_2(:,blade);
plot(x1,y1,'b.')
grid on
%The tip-timing data of sensor 1 for the selected blade
%is plotted against sensor 2

[TH,R] = CART2POL(x1,y1);
TH=TH-45*pi/180;
[X2,Y2] = POL2CART(TH,R);
figure(2)
hold on
plot(X2,Y2,'r.')
grid on
%The grid points are rotated -45 degrees

ao=[10 10];
options=foptions;
options(1)=1;
c1=sum(X2)/length(X2);
c2=sum(Y2)/length(Y2);
[a,options]=leastsq('ellipse1a', ao, options, [],
X2,Y2,c1,c2);
t=0:pi/100:2*pi;
plot(c1+a(1)*cos(t), c2+a(2)*sin(t), 'b')
%The matlab ellipse fitter is initiated

a_r = a(2)/a(1)   %Ellipse axis ratio
ssr_1 = -7.2264*a_r^3 + -21.82787*a_r^2 + 119.08946*a_r + -
0.16976
ssr_2 = -7.28363*a_r^3 + -21.82579*a_r^2 + 119.15622*a_r +
179.82559
%The two sensor separations, derived using Heath's method,
%are calculated in degrees of resonance.

hold off
```

APPENDIX C2. MATLAB IMPLEMENTATION OF TEST DATA GENERATOR

```
clear all;
%All previous variables are cleared.

in1 = input('Enter the name of the x ASCII input file with
its extension:');
xo = load (in1);
in2 = input('Enter the name of the y ASCII input file with
its extension:');
yo = load (in2);
%The time and rpm vectors are reused from existing run-down
%files.  The old files to be used are entered using the
%above expression.

sz=size(xo);
L=900;
sig=200;
ta=0:.25:(sz(1)/4);
y=3.033*exp(-.5*((yo(:,2)-
L)/sig).^2).*sin(ta(1:sz(1)))'+.5*rand(size(ta(1:sz(1))))';
x=10*exp(-.5*((xo(:,2)-
L)/sig).^2).*cos(ta(1:sz(1)))'+.5*rand(size(ta(1:sz(1))))';
%This segment of code implements an error function centered
%about 900 rpm to simulate the existence of the second
%engine order resonance.

ao=[10 10];
options=foptions;
options(1)=1;
c1=sum(x)/length(x);
c2=sum(y)/length(y);
[a,options]=leastsq('ellipse1a', ao, options, [],
x,y,c1,c2);
figure(1);
plot(x,y,'b.'), hold on, grid on
t=0:pi/100:2*pi;
plot(c1+a(1)*cos(t), c2+a(2)*sin(t), 'r')
hold off
%An ellipse is fitted to the artificial data to check its
%validity.

[th,r] = CART2POL(x,y);
th=th+45*pi/180;
[x2,y2] = POL2CART(th,r);
figure(2);
plot(x2,y2,'r.')
```

```
grid on
%The data is rotated 45 degrees in order to mimmick the
%appearance of actual test data.

x3=x2+2069.1;
y3=y2+4706.6;
%Average blade positions are added to make the data appear
%more realistic.




A1 = [xo(:,1) xo(:,2) x3(1:sz(1),:)];
A2 = [yo(:,1) yo(:,2) y3(1:sz(1),:)];
dlmwrite('dat1a.aa1',A1,'\t')
dlmwrite('dat1a.aa2',A2,'\t')
%The artifical data is written to the files listed above.
```
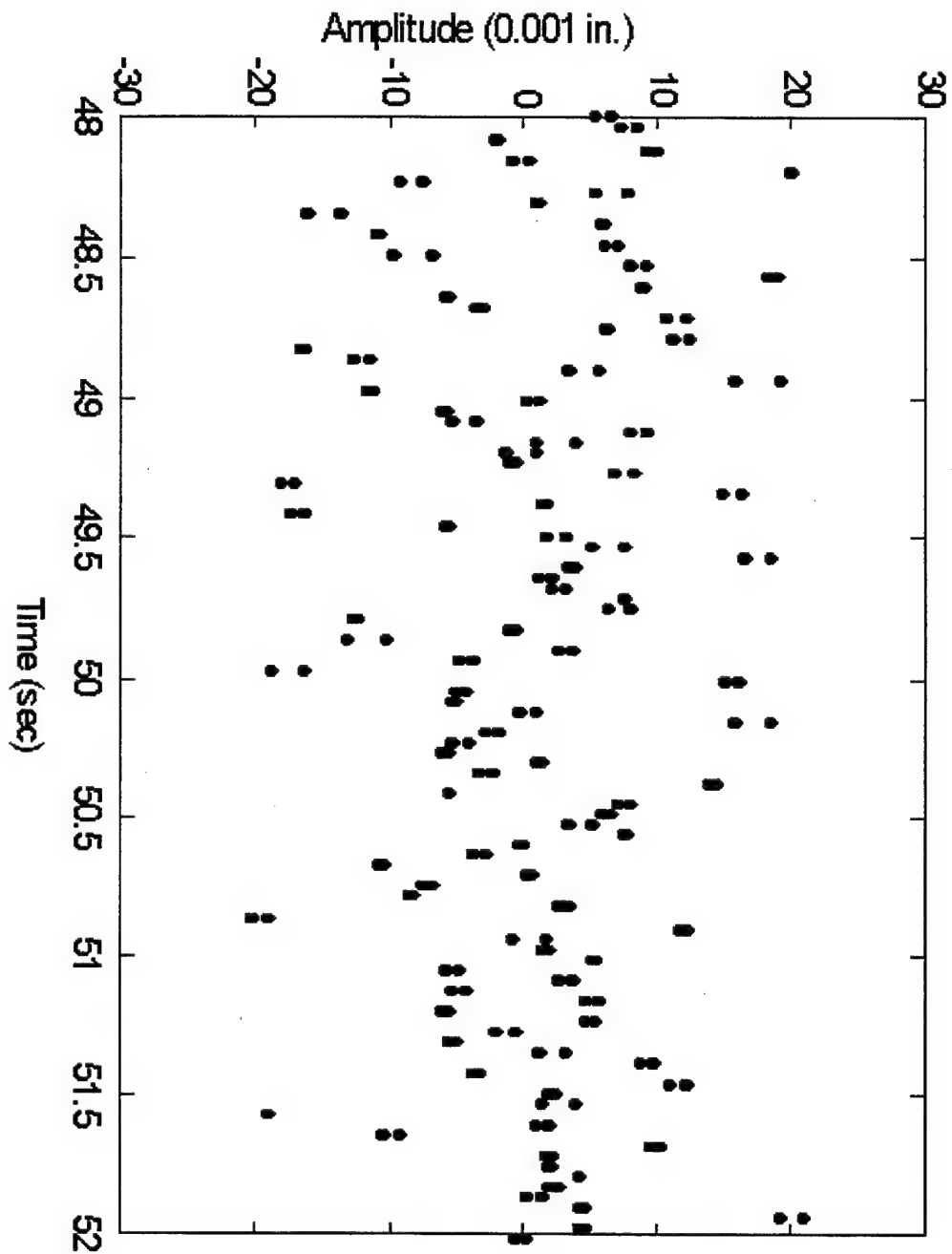
APPENDIX D2. AMPLITUDE VERSUS TIME AT CONSTANT SPEED:
ALL BLADES (30)

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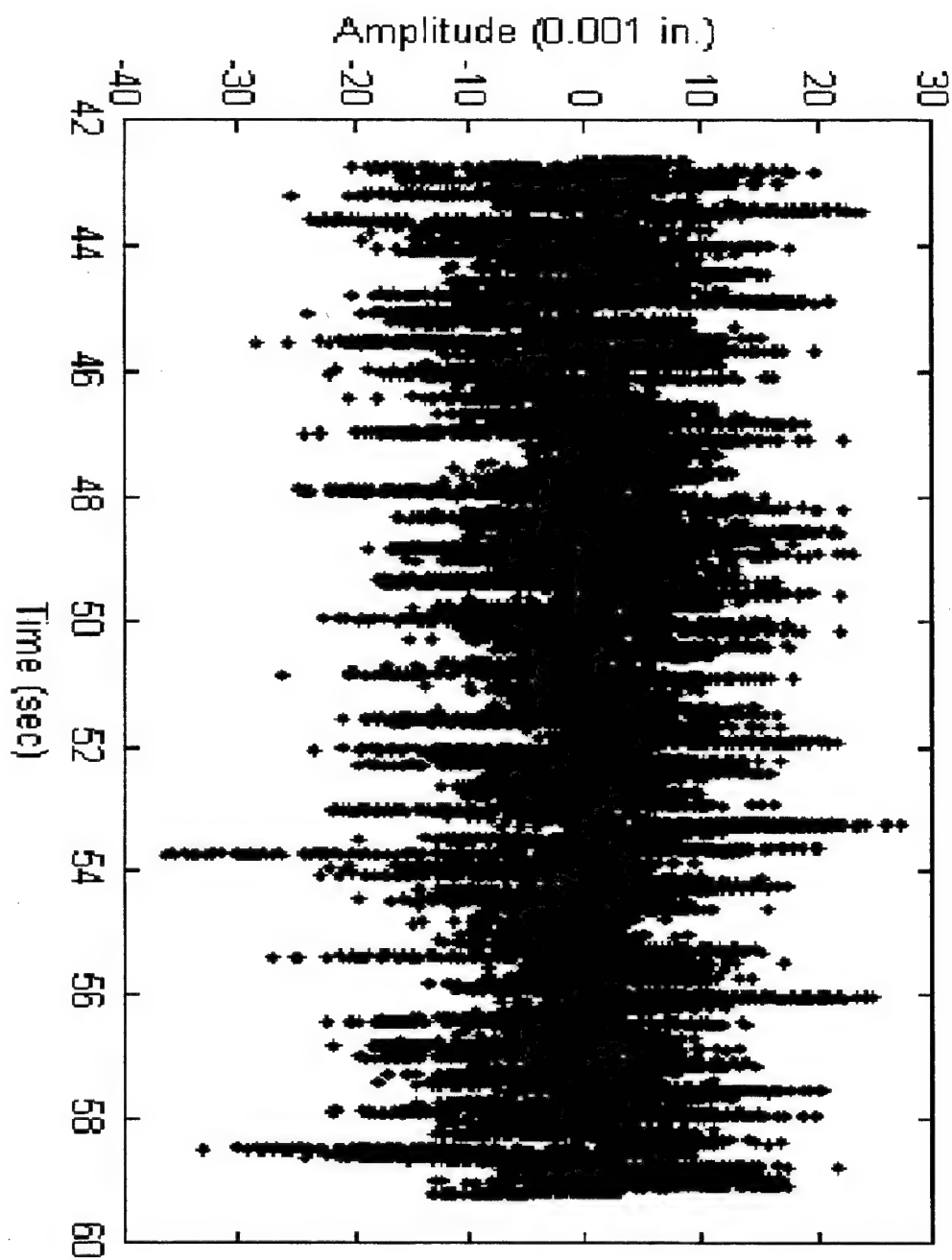
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